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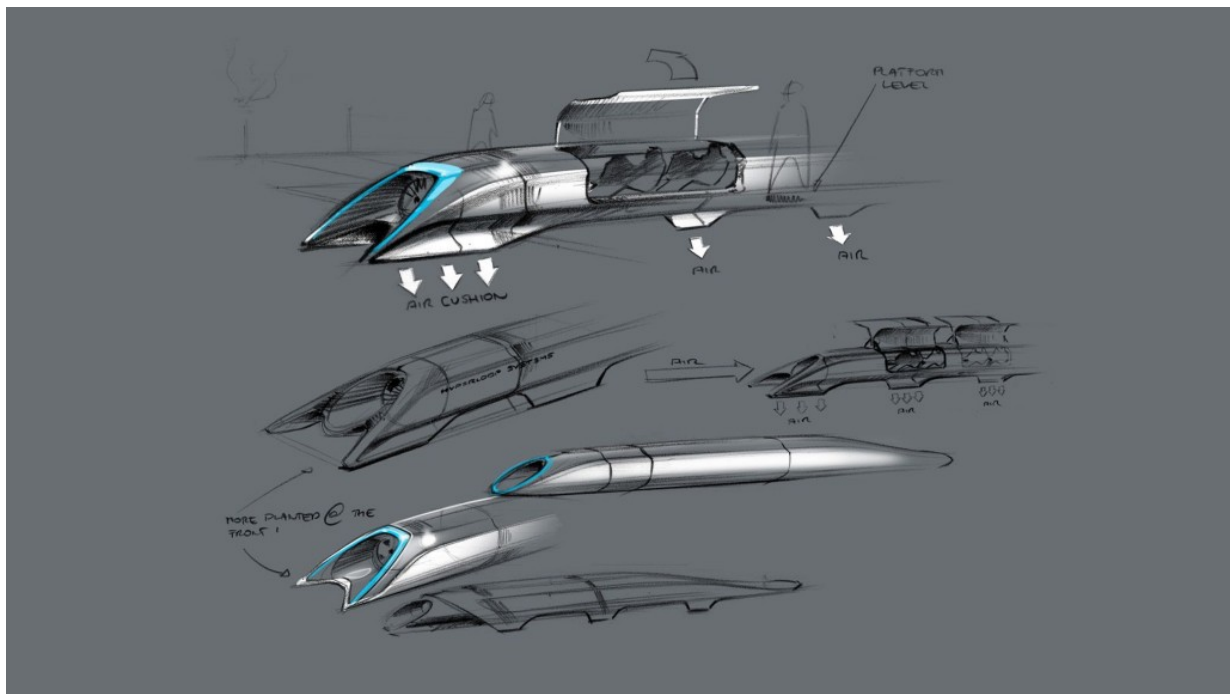
TECH + ENGINEERING

Promise and Perils of Hyperloop and Other High-Speed Trains

By Tim De Chant on Tue, 13 Aug 2013

Flipping through Elon Musk's proposal for the "hyperloop"—his vision for the future of transportation—you're left with an impression of thoroughness. It clocks in at 57 pages (http://www.spacex.com/sites/spacex/files/hyperloop_alpha-20130812.pdf). It's full of futuristic illustrations, schematics of air pressure systems, ledgers of estimated costs, and maps tracing a route between San Francisco and Los Angeles. There are references to Linux, an aerodynamic principle known as the Kantrowitz limit, and orbital welders. It's clear that Musk, who is the CEO of electric car maker Tesla Motors and rocket company SpaceX, has put a lot of thought into the plan.

Musk is selling the hyperloop as "a fifth mode after planes, trains, cars and boats." In reality, it owes a great debt of gratitude to that second mode, trains. And while Musk suggests that his untested system is good enough to replace trains, it's up against some stiff competition. Today, we have high-speed rail and magnetic levitation trains that are speedy, efficient, and—perhaps most important—proven.



Conceptual drawings of hyperloop capsules

"It's still too far out there in terms of being shown to be viable," says Dean Peterson, a senior scientist at the Los Alamos National Laboratory and former director of the Super Conducting Technology Center there, where he worked on maglev trains. "It has potential," he adds, "but some of his concepts still need further work."

The basic concept of the hyperloop is a pair of elevated steel tubes through which capsules carrying 28 passengers glide along at up to 760 mph on extraordinarily thin cushions of air. Capsules would be accelerated via linear motors, the same technology used in maglev trains. Linear motors are just like regular electric motors that are cut open and laid flat; electromagnets embedded in the track create waves of magnetic fields that propel capsules down the tube. To speed things further, air would be pumped from hyperloop tubes down to 100 pascals, or one-thousandth of the air pressure at sea level, reducing wind resistance. The remaining air would be compressed and fed through skis that run the length of the undercarriage to levitate the train.

If it works as planned, Musk says a trip between San Francisco and Los Angeles would take 35 minutes. But, he also admits, it will be at least seven to 10 years before that's even possible.

A Century of Speed

Though Musk's hyperloop will run in a partial vacuum, it wasn't conceived in one. Over two centuries of rail transport have informed his proposed system's design, including over 100 years of running trains at triple-digit speeds. One of the first high-speed trains, the Empire State Express No. 999, reached a claimed 112 miles per hour in 1893. Ten years later, an electric train in Germany hit 131 mph, fast enough to be considered officially high-speed by today's standards. The race was on, and railroads and nations experimented with various forms of propulsion in the quest to become the fastest. Some record-holding trains were motivated by electricity, others by diesel. One outlandish 1929 German prototype was driven by a massive rear-mounted propellor spun by an aircraft engine.

But it wasn't until 1964 that high-speed rail truly entered the mainstream. That's when the first Japanese Shinkansen train carried passengers from Tokyo to Osaka. With a nose shaped like an airplane, the electric trains ran at 130 mph in day-to-day operations, fast enough to shave two-and-a-half hours off the trip. A little over a year later, they cut another 50 minutes. In the 1960s and 1970s, other countries dabbled with other approaches—including turbine-driven locomotives and even prototypes that ran on cushions of air—but the Shinkansen had shown the way. Today, all high-speed rail runs on traditional steel rails and is powered by electric current.



An original Shinkansen train, seen here near Tokyo in 1967

Tracks are integral to any high-speed system, as Musk's hyperloop proposal attests. Rails of high-speed lines are welded and polished smooth, eliminating gaps that shake the train and could cause a train to jump its tracks. Turns also have to be carefully engineered, as tight radii can cause fast trains to derail. (A Spanish train derailed in July when it entered an older section of track not engineered for high-speed running).



The latest Shinkansen train, the E6 series

The trains, too, are specially designed to make high-speed running safer and more comfortable. When tracks bend, some cars are built to lean into the turns, counteracting centrifugal force. And on many sections of track, automatic controls can slow trains down to safe speeds if their operators fail to do so. They're also protected against natural disasters. In Japan, during the 2011 Tohoku earthquake, sensors brought trains to a halt 15 seconds *before* tremors from the reached them. Decades of trial and error have gone into planning and building high-speed rail systems, making them one of the safest ways to travel.

Chasing Higher Speeds

In the years since the first Shinkansen left Tokyo, train speeds have been steadily increasing. Today, many lines zip passengers between cities at speeds up to 186 mph. Some experimental trains, like the current world-record holding TGV, have even exceeded 350 mph. But for practical purposes, 186 mph may be the upper limit for conventionally wheeled trains. One look at video footage inside the cab (http://www.youtube.com/watch?feature=player_detailpage&v=iaXEgvVmNA&t=349) of the record-breaking TGV reveals why—its great speed magnified vibrations from minor imperfections in the wheels and tracks. Vibrations of that intensity are manageable for short runs, but over years of service and thousands of trains, wear-and-tear can take its toll.

“We found that they had big problems with maintenance of the tracks because of the friction,” Peterson says. “The pounding of the wheels on the rails accelerated the deterioration of the equipment. Routinely achieving those high speeds without having to continually work on the track has been a problem.”

Which is why the Japanese, the pioneers of practical high-speed rail, are looking beyond steel tracks. An obvious successor is maglev. Maglev trains float above their tracks, suspended by a magnetic field. The only friction they encounter is wind-resistance. By eliminating the friction inherent in wheeled vehicles, they can achieve even higher speeds with lower maintenance costs, Peterson says.



The Transrapid maglev train uses electromagnetic suspension to lift itself above the track. Levitating electromagnets are on the lower part of the L-shaped arms that wrap around the track.

There are two main ways maglev trains stay hovering above their tracks. One is electromagnetic suspension. Trains that use this type have L-shaped arms that appear to grasp the tracks. Magnets in the tracks, on the train, or both pull the bottom of the arms up toward the track and push the rest of the train above the guideway. The German Transrapid maglev uses this approach. The Japanese use another method, known as electrodynamic suspension. At low speeds, it rolls on wheels. But above 20 mph, the train's superconducting magnets induce a magnetic field in the sides of the U-shaped guideway, lifting the train above the track.

Perhaps the most striking fact about maglev is that, unlike traditional wheeled trains, motive force can be provided by the tracks themselves rather than the train. On the Japanese maglev, for example, electromagnetic propulsion coils sit in the sides of the U-shaped track, behind the levitation coils. Superconducting magnets onboard the train are attracted to coils of the opposite pole and repelled by coils of the same pole. As the train moves, the track-mounted coils flip their polarity, producing waves of attraction and repulsion that keep things moving.



A prototype of Japan's superconducting maglev train, or SCMaglev. Superconducting magnets, which help to both propel and levitate the train, are located behind the large boxes on the sides.

Building propulsion magnets into the track makes the train lighter, faster, and more efficient. However, it does make the track more expensive to build. Japan's maglev is estimated to cost about \$191 million per kilometer, compared with an average of around \$24 million per kilometer for traditional high-speed rail. However, that doesn't take into account maintenance. "With maglev, because it's floating just like an airplane, it's more expensive to construct, but it requires less maintenance and has lower ongoing costs after you build it initially," Peterson says.

Germany, Japan, and the U.S. began researching maglev trains since the 1960s. The German effort bore fruit with the Transrapid system, which currently links Shanghai with its international airport. Japan has been running a test track for decades, and last November, JR Central, a main operator of Shinkansen lines in Japan, announced that they intend to build an operational maglev running between Tokyo and Nagoya that will open in 2027. In the U.S., Peterson was involved in a freight maglev project that sought to reduce truck congestion by whisking cargo from the ports of Long Beach and Los Angeles to a transfer station outside the city. The project was canceled before a prototype could be built. U.S. passenger maglev hasn't fared much better either, despite support from organizations like The Northeast Maglev.

Vactrains

The hyperloop has frequently been compared to a proposed mode of transportation called a vactrain, which is short for vacuum tube train. It's easy to see why. Vactrains run in low-pressure tubes to reduce wind resistance, just like the hyperloop. In fact, the hyperloop's only major difference from other vactrain concepts is its air cushion suspension—a concept which was explored separately by French engineer Jean Bertin in the 1960s and 1970s.

Before the hyperloop, the vactrain proposal that received the most attention was Swissmetro, a maglev train that would run in low-pressure tunnels to connect the major cities in Switzerland. Marcel Jufer, a professor emeritus at École Polytechnique Fédérale de Lausanne in Switzerland, has worked extensively on the Swissmetro concept. After reading through Musk's hyperloop proposal, Jufer was intrigued yet concerned, especially about the vacuum pump system. Swissmetro is designed to run at about one-tenth atmospheric pressure, which is a great deal higher than hyperloop's one-thousandth.

"At 7% of atmosphere, it's very easy to produce that low pressure," Jufer says. "It's relatively cheap. But to go under this limit, you have to have a series of second pumps. The second pump is more complicated, more expensive, and probably it's necessary to have three pumps in series to reach one-thousandth of the atmospheric pressure."

Jufer, for his part, is open to collaborating with Musk. "Why not?"

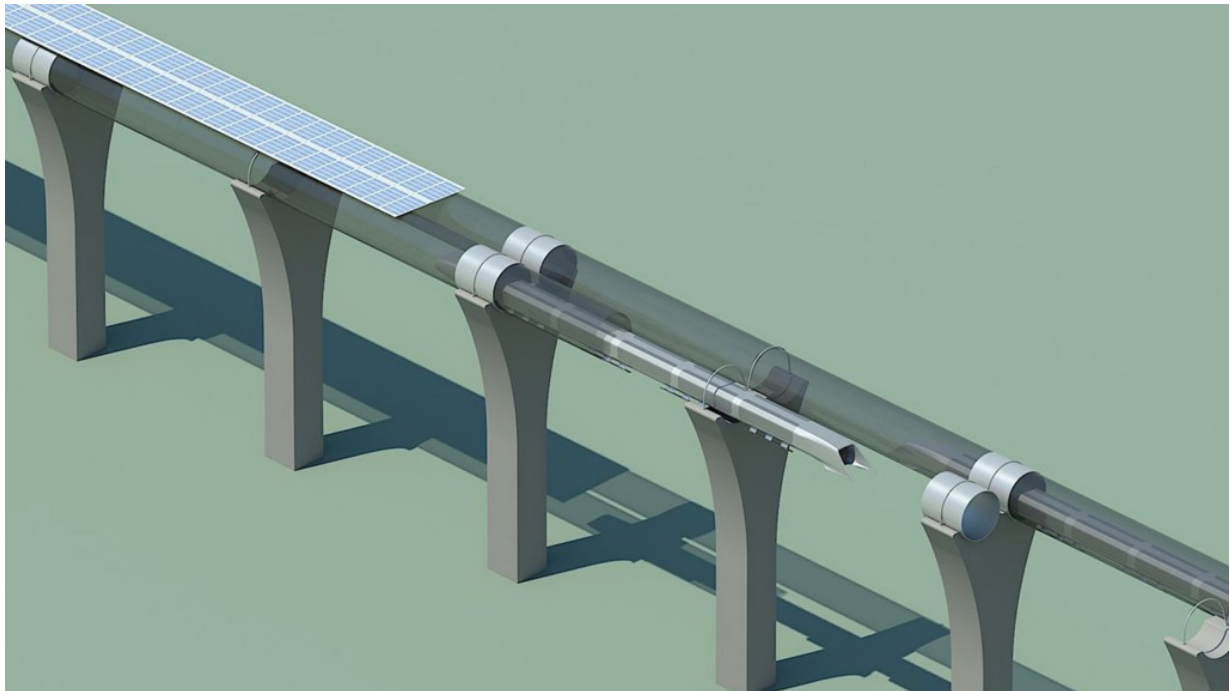
The low-pressure of the hyperloop also presents a problem when loading passengers, Jufer adds. “You need to have some kind of airlock system at the extremity or in the stations for passengers,” he says. “Doing this, you introduce a relatively important amount of air. Not a large amount, but it’s at atmospheric pressure, which means if you introduce 1 cubic meter of air at atmospheric pressure, it means it’s equivalent to 1,000 cubic meters of air at low pressure. It’s a relatively important disturbance.”

Beyond atmospheric and aerodynamic studies, the Swissmetro team has performed system-wide simulations of their concept. They also just completed a six-month preliminary investigation for the South Korean government, which is interested in linking its main cities at high-speeds. It’s unclear whether Musk’s hyperloop team has read the Swissmetro research papers, but many of them are freely available or easily accessible. Jufer, for his part, is open to collaborating with Musk. “Why not?” he says.

Beyond Megaregions

As it’s proposed, the hyperloop will serve a similar transportation function as high-speed rail and maglev, just on a grander scale. If we want to envision what the future could look like when hyperloop connects distant cities, all we have to do is study how high-speed rail has changed smaller regions today. The short answer is, pretty substantially.

Joseph Sussman, a civil engineer at MIT, studies the effects of high-speed rail on regional development. High-quality rail links, he says, create megaregions of cities that were once too far apart to be considered linked. Forging new megaregions can be an economic boon. “The idea here is one could have integrated labor markets, integrated commercial markets, that would create some economic stimulus,” he says.



This cutaway shows how hyperloop capsules would run in elevated tubes. Power would come from solar arrays sitting atop the structure.

“Over the years, there has been a lot of theory developed about labor markets,” Sussman continues. “If you can draw your labor from a broader pool, the prospects of matching up people with jobs in high-value segments of the economy, it’s a good thing. Rather than having some kid flipping hamburgers because he doesn’t have access to a more high-tech job—a computer programming job, let’s say—adding quality transportation to the mix gives that opportunity for him.”

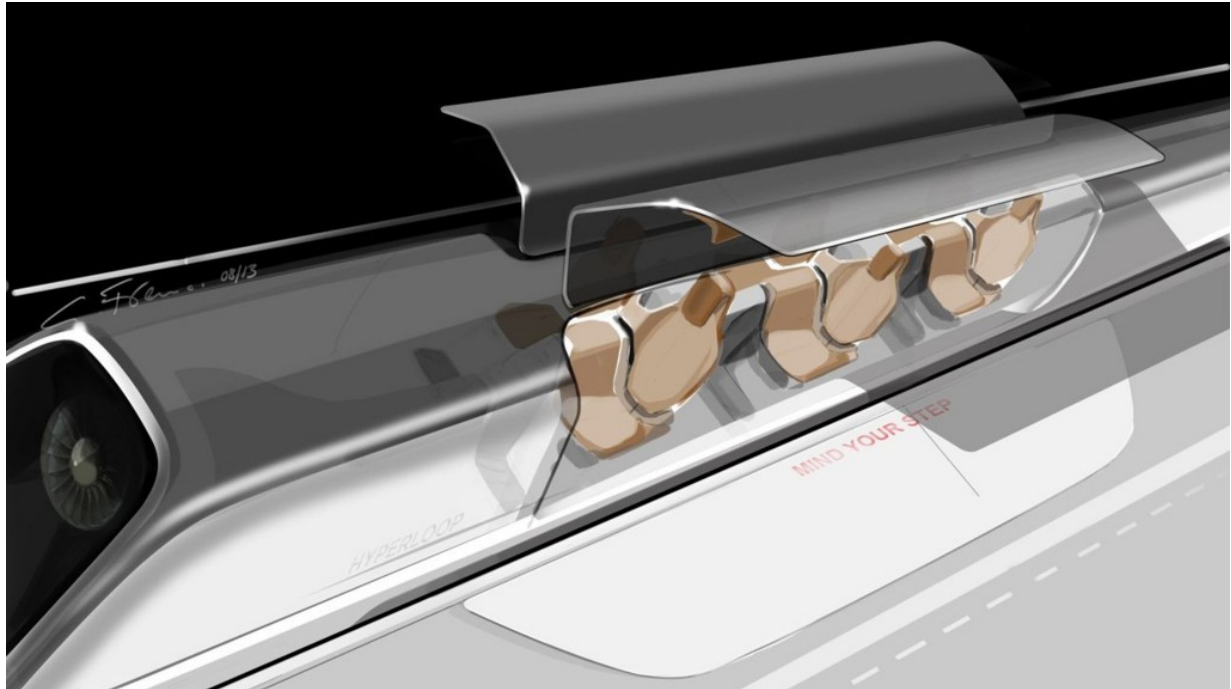
But creating a nationwide megaregion isn’t as straightforward as adding transportation links, Sussman says. When two distant cities are linked—with few to no stops in between—they create a discontinuous region. How do you govern such a thing? “We have enough trouble in American cities figuring out how to manage urban areas when one has the urban core in addition to the suburbs,” he says. “That’s hard to manage, and those are geographically connected.”

If built—and built extensively—the hyperloop could make jobs in major cities accessible from a vast region. Imagine living in Boston and commuting daily to a job in Philadelphia. The megaregions we discuss today could seem quaint by comparison.

Devil Is in the Details

The hyperloop is brimming with the sort of gee-whiz futurism that makes it easy to overlook the substantial challenges that still need to be ironed out. One hurdle which Musk glosses over is the matter of right-of-way. Elevating the tubes will certainly alleviate some of the property costs, but not all. While most of his proposed link runs down California's relatively straight Interstate 5, there will still be instances where land will have to be bought or rented to make for more gentle turns. Plus, any project like this is certain to spark protests. The aesthetics won't please everyone, and 760-mph capsules will probably make more noise than their steel tubes can contain.

On the engineering side, "one of the big issues for me would be the safety," Peterson says. For example, Musk and his team suggest that only 0.5 to 1.3 mm of air needs to pass between the skis and the tube. "Your tolerance on the tube becomes a real issue if it's only half a millimeter," Peterson says. "Even if it's 1.3 mm, it's still a question mark whether you can maintain the tube variation to that level." If skis were to strike the tube, it could make for an uncomfortable ride or, worse, lead to a crash, he adds.



An artist's impression of passenger access to a hyperloop capsule

Then there's the issue of safety during emergencies. Should a capsule become stalled, it'll eventually lose air pressure in the cabin. Oxygen masks will be supplied, but how long will they last? And what if, despite precautions, an earthquake rends a tube in two? "If you've had any kind of failure where you're facing one atmosphere of pressure—if a tube would fail? Boy, you hit that at 700 mph...my god," Peterson says.

Despite the obvious gaps that need to be addressed, Peterson is cautiously optimistic. "It's nice to see someone proposing something like this that advances transportation," he says. "I think we can continue to develop high-speed trains and still do this on at least a viability study, that's probably where this belongs right now. It may never go beyond that, but it's worthwhile exploring."

"What it shows to me," Peterson concludes about Musk and the hyperloop plan, "is that he is recognizing the need for a higher speed train system."

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